CONVEXITY AS A CUE FOR FIGURE-GROUND ASSIGNMENT: INVESTIGATING INHIBITION BETWEEN CONVEX AND CONCAVE REGIONS

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Abstract

Convexity is a potent cue in figure-ground assignment. Convex regions are often perceived as figure whereas concave regions are perceived as background. Peterson suggested that shape properties, such as convexity, compete for awareness on both sides of an edge. The side with the stronger figure cues wins and is seen as figure, and at the same time inhibits the other side of the edge, which is seen as ground. The current study employs Townsend's capacity coefficient to investigate whether a convex contour inhibits the processing of a concave contour when they are presented simultaneously. The results suggest that inhibition may occur, but can appear also when two convex areas or two concave areas are presented. The capacity coefficient may be affected by either inhibitory processes or by actual limitations in processing capacity, so further investigation is needed to discern the two.

Visual perception begins with cluttered two dimensional (2D) projections of the three dimensional (3D) world on the retina. People then organise this clutter through a process known as *figure-ground* segregation. The shaped entities, or *figures*, are separated from adjacent regions by their bounding edges. The adjacent regions are often shapeless near the borders of the figures and seem to continue behind them as backgrounds; hence, they are called *grounds*. Figure-ground distinctions are fundamental to the visual perception of objects and are essential for just about every behavioural task (e.g., Peterson & Salvagio, 2008).

Much of the literature on figure-ground perception focuses on identifying those properties, or 'cues', that affect the likelihood that a region will be seen as a figure (Peterson & Skow, 2008). For example, regions that are small, closed, convex, and/or symmetric are likely to be seen as figures (Pomerantz & Kubovy, 1986), whereas adjacent regions that are larger, open, concave, and/or asymmetric are likely to be seen as grounds. The current study focuses on *convexity*, which is defined as having an outline or surface curved like the exterior of a circle or sphere. A polygon that is convex does not have any angles greater than 180^{o}.

Convexity is a potent cue. Detecting differences between concave and convex contours is vital for the visual system, and there is a prior expectation favouring convexities as figure (e.g., Kanizsa & Gerbino, 1976). Kanizsa and Gerbino showed that convexity is one of the strongest determinants of figure assignment, even when pitted against other factors such as symmetry. Bertamini and Lawson (2008) found that shape affected response times in a depth discrimination task; when the convex side of a contour was specified as in front, responses were significantly faster. Pomerantz and Kubovy (1986) suggested that convexity is an important cue because convex edges are more common in the environment than concave edges. Many natural stimuli are convex whereas only a few objects are completely concave.

How is convexity used to decide what is figure and what is background? Peterson and colleagues (e.g., 2008a, 2008b) proposed a model in which shape properties (convexity, symmetry, closure, etc.) from two sides of an edge are processed in parallel in an interactive shape pathway. Shortly after edges are detected, the shape properties on either side of the edge compete for awareness, so as the shape properties on one side increase in strength or number, inhibition of shape properties on the other side also increases. The side of the edge with the strongest shape properties wins the competition and is therefore perceived as the ‘figure’. The losing side is suppressed and is therefore seen as the ‘ground’. The current study investigates Peterson’s model of figure-ground perception by testing whether inhibition occurs between convex and concave regions, using a measure for workload capacity known as the *capacity coefficient*, or C(*t*). It is based on the entire response time distributions and can inform researchers about potential inhibitory connections between two (or more) information-processing channels. C(*t*) is used within the redundant target design that has been successfully used in vision research (e.g., Miller, 1982; Townsend & Eidels, 2011), and is outlined next.

In a *redundant target design*, a target item can appear on one location (say, left), on another (right), or on both (or not appear at all), and participants respond affirmatively if they detect at least one target. The experimenter compares response times (RTs) on trials where a single target is presented versus both targets presented. RTs are typically faster, on average, on trials containing two targets versus one target – the *redundant target effect*. The critical contrast is calculated by comparing mean RT on the faster of the two single-target conditions versus mean RT on the redundant (double) target condition (Eidels, Townsend, & Pomerantz, 2008). This means that the redundant target effect is easily subjected to statistical testing of significance. However, faster performance on redundant targets compared to the single target trials does not give a clear indication of whether the channels are independent or dependant (an inhibitory model is based on dependant parallel processing). This is because ordinary parallel processing, where channels are independent (there is neither facilitation nor inhibition), and even parallel models with moderate inter-channel inhibition can lead to redundant target superiority (Eidels, Houpt, Altieri, Pei, & Townsend, 2011). The current study employs the capacity coefficient, C(*t*), a fine-grained measure of performance that can detect slight deviances from the performance predicted by an independent-channel system. Peterson’s model predicts that when both convex and concave contours are presented together, convexity inhibits the complementary concave edge, making processing capacity limited in comparison to when convex is presented alone, or concave alone. To test the model, we designed experiments that allow the calculation of C(*t*) with convex and concave stimuli.

In the experiments, on any given trial convex and concave contours can be presented simultaneously (AB; a redundant target trial), convex alone (single target A), concave alone (single target B) or neither (no target, which includes two distractors). To calculate C(*t*), we measure RTs on single and double target conditions and estimate, for each condition, the cumulative distribution function, F(*t*), and the survivor function $S(t)=1-F(t)$. The integral of the hazard function, H(*t*), is a log transform of S(*t*), and gives the cumulative amount of work done up to that point of time. By dividing the integrated hazard function of the redundant target condition by the sum of the integrated hazard functions from the single target conditions, the capacity coefficient can be estimated, $C(t) = H_{AB}(t)/[H_A(t) + H_B(t)]$.

If two processing channels – one for target item A and the other for B – are independent, then each channel should perform in the presence of the other just as well as it performs alone. The prediction of such a model is *unlimited capacity*, $C(t)=1$. However, if channel A inhibits channel B or vice versa, then the efficiency of processing in the system is impaired compared to a parallel and independent system. This results in *limited capacity*, $C(t)<1$, which is the prediction of the inhibitory competition model. According to Peterson’s model, when convex and concave regions are presented together the former inhibits the latter. Inhibition *should not* occur if a convex region is presented alone, or if a concave region is presented alone. Thus, when comparing processing efficiency with two target-items – convex and concave – versus processing of each alone, we expect to find impaired performance with double-target displays. The consequence is limited capacity, $C(t)<1$.

In the current study we measured the presence and amount of inhibition caused by convexity by calculating the capacity coefficient, C(*t*), for the detection of convex and concave items. In the experimental condition we present, on each critical trial [there are also no target trials that are not taken into account in the calculation of C(*t*)], a concave region, a convex region, or both. We then measure RTs and calculate the capacity coefficient. The inhibition model predicts performance impairment when a convex region and a concave region are simultaneously displayed, $C(t)<1$. Importantly, channels can also slow down because of true capacity limitations, and not purely because of inhibition (Townsend & Wenger, 2004). To control for capacity limitations, we added two control conditions, again with single- and double-target trials. In the first control condition, 'convex only', all presented regions, on both single and double target stimuli, are convex. In the second control condition, 'concave only', all presented regions are concave. The model predicts that in the control conditions two targets from the same type will not inhibit each other and capacity will not be as limited as it is predicted to be in the experimental (mixed convex-concave) condition. Experiments 1 and 2 both tested convexity using the redundant-target task and C(*t*), and were identical in design and procedure but used slightly different stimuli.

Experiment 1

Method

Participants. 20 participants, all with normal or corrected to normal vision with a mean age 21.6 and standard deviation 1.67. All participants were right handed and seven were male. They received a compensation of $10 for a one-hour session.

A*pparatus.* Displays were presented on a 17'' CRT monitor with a screen resolution of 1024x768, using IBM compatible computer. Stimuli were presented at the centre of the screen on a medium grey background (red, green, and blue values were all 122 on a 0-255 scale). Participants used a Cedrus Response pad (RB-830 model) to initiate each trial and to make their responses. The stimuli were displayed using Presentation software which also recorded responses and response times.

Stimuli and design. Each participant completed three conditions (stimulus types): mixed convex-concave, convex only, and concave only. The conditions were separated in different blocks. Within each condition displays consisted of double targets, single target A, single target B, and no target. The displays were mixed within blocks. We used a 2x2 within subjects design, where two target positions, on the left and right hand sides (target A and target B, respectively) could be occupied by a target or not. It is challenging to present a convex side of an edge without its complementary concave edge. Example stimuli, in the top row of Figure 1, demonstrate our attempts to overcome this problem, as well as eradicating size and symmetry as confounding visual cues. In the graphics program Blender we created rectangular frames, 12^{o} in width and 6^{o} high, each divided horizontally into 3 equal rectangles. This display served as the no target stimulus (Figure 1, right side). To create the convex and concave stimuli, boundaries of the first and third regions were altered to either be concave or convex. Concave and convex edges were made by concatenating five arcs of ellipses that randomly varied in size and orientation, while marinating equal areas for each of the three regions. We created enough variations as to exclude the possibility of repeating the same stimulus. We generated three types of stimuli, one for each experimental condition. The example stimuli presented in Figure 1 are from the convex-concave mixed condition. In the *convex only* condition edges on both sides would either be flat (no target) or convex, and similarly on the *concave only* condition edges would be either flat or concave. Within each condition there could be four display types, which are illustrated in Figure 1: double targets, with two target contours (in this example – one convex and one concave), single target A, with a contoured form on the left and a flat form on the right, single target B, with a flat form on the left and contoured form on the right, and no target, with two flat forms.

Procedure. Participants were tested individually in a dimly lit room, after 5 minutes of darkness adaptation, and were seated 50cm in front of the monitor. The study consisted of 36 oractice trials in three blocks of 12 trials each, and a total of 960 experimental trials in six blocks of 160 trials each. Experimental conditions (mixed convex-concave, convex only, concave only) were blocked, with each condition presented in two consecutive blocks. Participants were given a two-minute break between blocks. Conditions were counterbalanced for order. Display types (double target, single target A, single target B and no target) were mixed within block and presented in random order with equal proportion. Participants were instructed to respond affirmatively by pressing the left key on the Cedrus Response box with their left index finger, if either or both of the features that were defined as concave or convex appeared. Otherwise, if a display had no concave or convex contours (i.e., a straight edge form) participants were to respond negatively by pressing the right key with their right index finger. Participants were asked to respond as quickly and as accurately as they could.

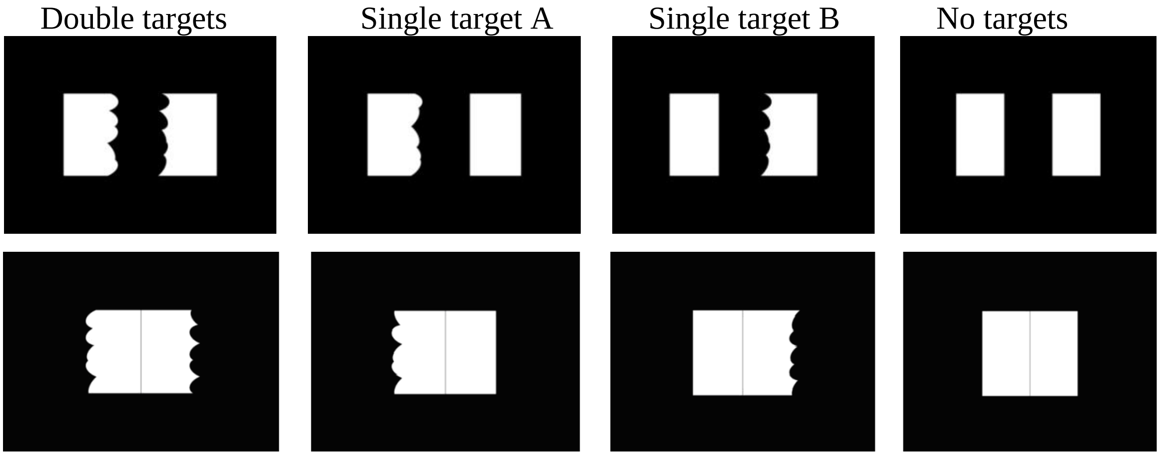

Figure 1. Example stimuli used in Experiments 1 (top row) and 2 (bottom row), in the convex-concave mixed condition.

Results and Discussion

RTs and the redundant-target effect. A paired samples t-test revealed a significant redundant-target effect of 17.1 ms in the convex-concave mixed condition: double-target RTs (M=355.6) were significantly faster than the fastest single target, $t(19)=-6$, $p<.001$. Recall, however, that an independent, unlimited capacity (neither inhibition nor facilitation occurs) parallel model predicts faster responses on double target trials compared to single target trials, simply because of statistical considerations that are due to target redundancy (‘statistical facilitation’, e.g., Townsend & Eidels, 2011). Further analysis was therefore conducted.

Capacity coefficient. The top row of Figure 2 illustrates the capacity coefficient across all participants, for each of the three conditions of Exp. 1 (convex-concave, convex alone, and concave alone. Recall that $C(t)=1$ is the benchmark with channels that are processed independently and in parallel. If inhibition occurs on double target displays because a convex target suppresses the concave target, capacity should be limited, $C(t)<1$. The top-left panel of Figure 2 shows that capacity was mostly limited for the convex-concave stimuli. This supports the notion that the convex contour may be inhibiting the concave contour, as suggested by the inhibition model. But is inhibition the only explanation for limited capacity? Recall that $C(t)<1$ could also be a product of true capacity limitations at the item level (Townsend & Nozawa, 1995). We investigate this alternative explanation by examining $C(t)$ on the convex only and concave only conditions. According to the model, a convex edge should not inhibit another convex edge, and a concave edge should not inhibit a concave edge. Thus, these conditions should not be susceptible to inhibition and capacity should not be as limited as in the mixed condition. $C(t)$ values for the convex only and concave only conditions are presented in the top-middle and top-right panels of Figure 2, respectively, and are qualitatively similar to the mixed condition. Thus, capacity limitations are not exclusive to displays where convex regions presumably inhibit concave regions. This suggests that some other capacity limiting effect may account for the limited capacity observed with convex-concave stimuli. Generating purely convex or purely concave regions is challenging since a convex edge cannot be presented without its complementary concave edge (and vice versa). In that case our single-target displays may be perceived as already containing two targets (say, a concave edge and its convex complement), which may have contaminated our capacity calculations. In Exp. 2 we altered the stimuli to minimize effects of complementary regions.

Experiment 2

Method

The design and procedure were identical to Exp. 1. The stimuli were the same except that the convex/concave edges were 'flipped' from the inside to the outside edge, and the distance between the two forms was reduced to a hairline. Example stimuli (convex-concave) are shown at the bottom of Figure 2. Twelve individuals, with a mean age 23.8 and standard deviation 4.09, participated for $10 per session. Two were left handed and seven were males.

Results and Discussion

Redundant target effect. A paired samples t-test showed a significant redundant target effect of 18.4 ms: participants responded faster when presented with double targets (*M*=363.4), in comparison to the fastest single target, $t(11) = -4$, $p<.01$.

Capacity coefficient. As can be seen at the bottom of Figure 2, most C(*t*) values are below unity, implying limited capacity that could result from inhibition between two opposing shape properties (convex suppressing the concave, a-la the inhibition model). However, the same C(*t*)<1 pattern that was observed for the mixed condition (bottom-left panel) was also documented for the convex only (bottom middle) and concave only (bottom right) conditions, suggesting that it is perhaps not just a convex to concave inhibition that limits the C(*t*) estimates, but also other, more general capacity limiting effects.

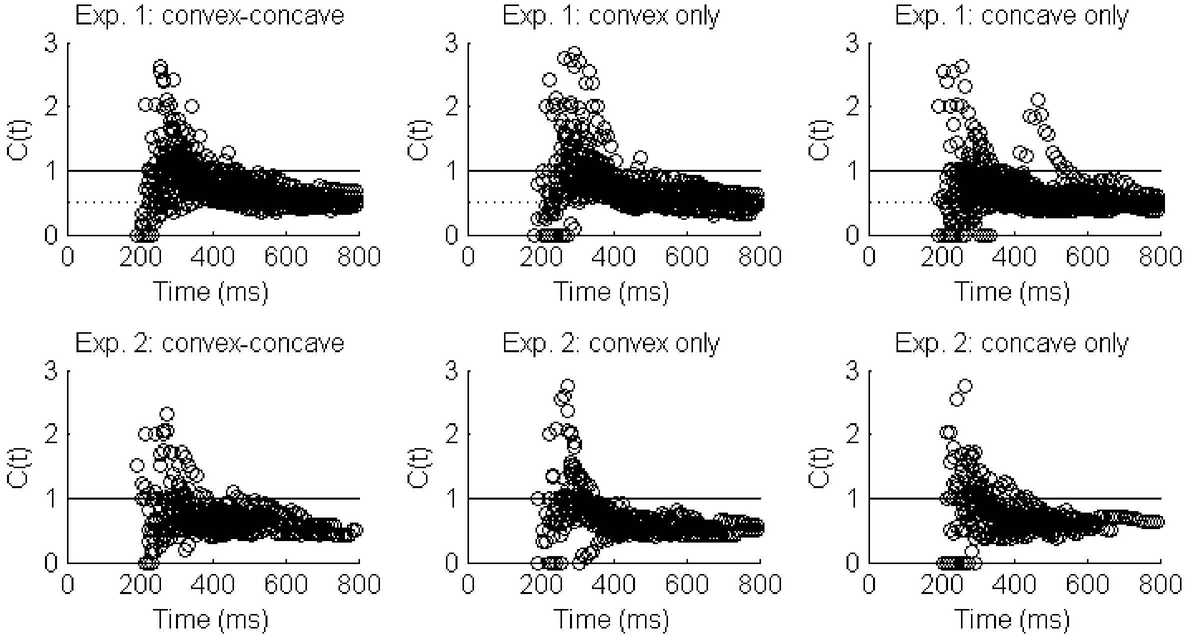

Figure 2. Capacity coefficients from Experiment 1 (top) and 2 (bottom), for the three conditions: mixed (convex-concave), convex alone, and concave alone. C(*t*) was calculated individually for each participant, and data from all participants are plotted on the same figure.

Conclusions

Convexity is a potent cue for figure assignment. In a pilot study we replicated Peterson and Salvagio's (2008) findings and showed that participants perceived the figure on the convex side of an edge more often than on the concave side (75.4% of the trials in our pilot study, 89% in theirs). Pomerantz and Kubovy (1986) suggested that convexity is important because most natural stimuli are convex (from a tiny grain of rice, through oranges and apples, to planets). According to the inhibitory competition idea (e.g., Peterson & Salvagio), strong cues for figure assignment on one side of an edge (convex) make this side salient and seen as a figure, which in turn inhibits the other side (concave) and deem it ground. We used Townsend and Nozawa's (1995) capacity coefficient to test inhibition between convex and concave attributes. We discovered consistent limited capacity [$C(t)<1$] when convex and concave targets were presented simultaneously, as predicated by the inhibition model. However, capacity was mostly limited also when two convex targets were presented together, or when two concave targets were displayed. Thus, the limited capacity observed in this study may be either the consequence of any two convex/concave attributes presented together (not just one convex and one concave region), or driven by actual limitations in processing capacity (e.g., limited processing resources as more attributes are presented for view). Further investigation is needed to discern between the two explanations.

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